ARKIV FÖR FYSIK Band 1 nr 10

Communicated 9 February 1949 by Erik Hulthén and Rolf Sievert

Investigations of the pulse-distribution of an RCA multiplier phototube

By Richard Westöö and Tor Wiedling

With 10 figures in the text

In a multiplier each photoelectron ejected from the cathode gives rise to an avalanche of secondaries. As they reach the anode a negative pulse is obtained that can easily be registered and measured. As a result of the statistical nature of the amplification in the multiplier, the pulses show a broad distribution in magnitude. Pulses are observed even if the tube is kept in the dark. They are considered to arise from thermionic emission.

Engstrom[1] determined the pulse-height distribution of a commercial RCA multiplier both in the dark and on irradiation with light, by visual observation of the pulses on a cathode-ray oscilloscope. In the present investigation the pulses have been photographed from the oscilloscope screen at various voltages and temperatures of the multiplier. The shape of the distribution graphs obtained is discussed and information gained concerning temperature and voltage dependance of the tube's operation. The data are compared with previous results from galvanometer measurements.

Experimental

One commercial multiplier 931 A manufactured by RCA was used throughout the experiments.

The variable and stabilized high tension set was of the Evans[2] type. The voltage was distributed to the electrodes from a potential divider after additional filtering as shown in Fig. 1.

The multiplier was mounted in a brass container with double walls to permit cooling. In order to make the cooling of the electrodes effective, the potential divider was placed outside the container and the conducting wires brought out through long channels in the brass, though this construction entailed an inconvenient increase in the capacitance of the output. To prevent condensation of water the lid of the container was made to fit tightly to the wall and the air enclosed was dried with phosphorus pentoxide.

In the beginning of the investigations trouble was caused by the appearance of pulses when the apparatus was operated with the multiplier removed. These

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[1] R. W. Engstrom, J. O. S. A. *37*, 420 (1947).

[2] R. D. Evans, Rev. Sci. Inst. *5*, 371 (1934).

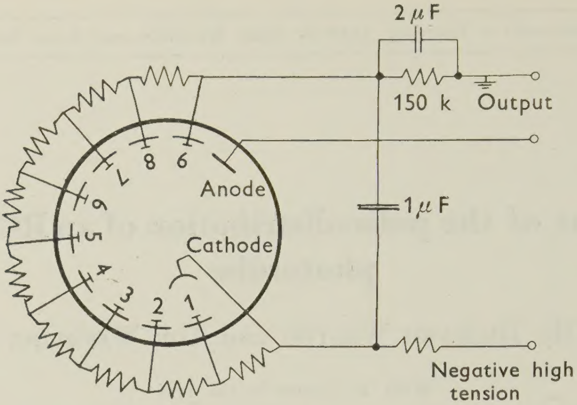

Fig. 1. Wiring diagram of the multiplier. Each resistance 100 kΩ, unless specified.

pulses increased with accelerating voltage as would be expected for real multiplier pulses, but seemed to be of a greater amplitude. It is thought that these pulses were due to a discharge on the surface of the commercial tube socket from the anode terminal to the adjacent cathode terminal that is kept about a thousand volts lower in potential. As a matter of fact, cleaning the socket reduced the number of pulses.

If the anode lead was disconnected from the socket and isolated from the high tension leads by polystyrene the false pulses decreased in magnitude but did not vanish. MARSHALL, COLTMAN, and BENNETT[3] seem to have encountered similar disturbancies. It might be that pulses are transmitted capacitively from the dynode leads that fluctuate in potential due to discharges along the socket, the bleeder-mounting, or the insulation of the wires.

The resistances were therefore remounted on good insulators, the wires drawn through pyrex tubes and ceresin into the brass container, and the socket removed. After these improvements no pulses could be detected. The base of the multiplier was now cut away, the glass cleaned, and the tube soldered to the leads. For additional security the anode lead was screened and dynode 9 surrounding the anode connected to earth by a condenser.

In order to determine the origin of pulses the electron beam was defocused now and then during the experiments. If this was done by connecting dynodes 4 and 5 without changing the tension between anode and cathode a few pulses were observed. They appeared, however, only at high voltages in the tube and were much smaller than those with normal dynode wiring. Connection of dynodes 3 and 4 gave a less marked decrease in the number of pulses, which agrees with RAJCHMAN and SNYDER's[4] graphs.

The result of this test indicates that in the new mounting of the tube the pulses at normal dynode wiring do not originate from discharges along surfaces outside or inside the tube.

Emission of one photoelectron results in the collection of an avalanche of electrons on the anode — according to SARD[5] during a time of the order of 10^{-9} secs. In the preamplifier this charge is transported to ground through a leak of 10^8–10^7 ohms. The steep front of such pulses is beautifully shown by COLLINS[6] with a microoscillograph. The step pulse is applied to the floating grid of a 6AK5 by a condenser. To ensure quiet operation, the voltages of this tube were supplied by batteries. The high and low frequency responses of the preamplifier were equal with a time constant varying between 5 and 20 μsecs in the different experiments.

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[3] F.-H. MARSHALL, J. W. COLTMAN, and A. I. BENNET, Rev. Sci. Inst. *19*, 744 (1948).

[4] J. A. RAJCHMAN and R. L. SNYDER, Electronics *13*, 20 (Dec. 1940).

[5] R. D. SARD, J. Appl. Phys., *17*, 768 (1946).

These values were chosen so as to give a good signal-to-noise ratio which is important when the multiplier is operated at reduced voltage. The amplifier could not be made faster if the pulses were to be recorded on the oscilloscope, and not much slower if excessive overlappings of the pulses were to be avoided with the multiplier at room temperature. So the time constants used are also to be considered as a compromise between these two requirements.

The pulses were fed to a linear amplifier and photographed from the screen of a Cossor double-beam cathode-ray tube in the absence of a tube with higher brilliancy. The writing-speed was however considerable as the screen was blue fluorescent and the trace pictured with a Zeiss objective R-Biotar f:0.85, $F = 4.5$ cm on Ansco Triple S Pan 16 mm film. The motion picture camera was a Bolex-Paillard model H adapted for continuous recording. Some recordings are shown in Fig. 10. The second beam of the tube was used for time-marking. The step voltage of the multiplier anode corresponding to a certain height of the traces on the film was determined by introducing signals from a square wave generator with an attenuator at the input of the preamplifier.

In order to obtain the pulse-height distribution, a large number of pulses had to be measured on the film and grouped in convenient intervals of magnitude.

Expected distribution of pulses

An electron emitted from the photocathode will be accelerated in the field from dynodes 1 and 2 in a direction so as to strike dynode 1. On impact a number of secondary electrons are produced. According to a discussion by ZWORYKIN and MORTON[7] it is reasonable to assume that the probability $p(z)$ that z electrons are ejected by one incident particle is given by the Poisson equation

$$p(z) = \frac{R^z}{z!} e^{-R}$$

where $R = \bar{z}$, the mean multiplication factor.

This group of z particles moves to dynode 2 and produces new electrons by secondary emission. And so on. The RCA 931 A contains nine multiplying steps, so the mean number of electrons collected on the anode will be R^9 for one primary electron from the cathode, if we neglect electrons lost by imperfect focusing.

n may be the number of electrons in a group starting from electrode number q in a multiplier and N the number starting from electrode $q+s$. If it is assumed that n varies about the mean $\bar{n}$ by the Gaussian error-curve with a root mean square deviation $\sqrt{\bar{n}}$, ZWORYKIN and MORTON show that the root mean square deviation of

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[6] G. B. COLLINS, Phys. Rev., *74*, 1543 (1948).

[7] V. K. ZWORYKIN and G. A. MORTON, Television, 3rd ed. 1945, Chap. I.

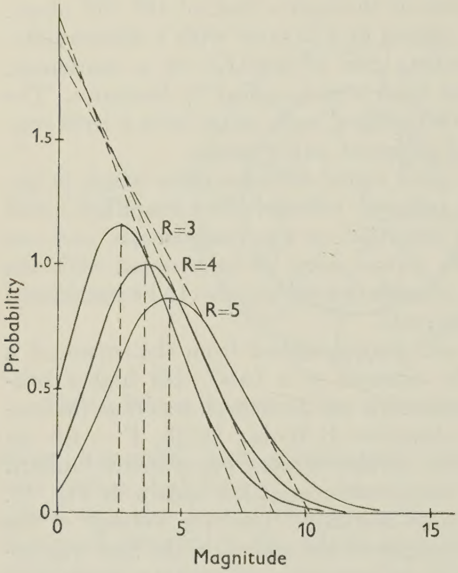

Fig. 2. Broadened Poisson distribution for $R = 3$, 4, and 5.

N from the mean value $\bar{n} R^s$ will be $\sqrt{\bar{n} R^s (1 + R + \cdots + R^s)}$. Repeated secondary emission, therefore, increases the relative root mean square deviation[8] from $\frac{1}{\sqrt{\bar{n}}}$ to approximately $\frac{1}{\sqrt{\bar{n}}} \sqrt{\frac{R}{R-1}}$.

Approximately the same relative broadening ought to take place if the distribution for the electrons that leave dynode 1 follows Poisson's formula. Under this assumption, the curves of Fig. 2 are drawn for $R = 3$, 4, and 5. They show the relative probability for a certain number of the electrons in avalanches striking the anode, i. e. the expected distribution in magnitude of the output pulses.

Experimental distribution of photo-pulses

In order to reduce the number of dark-pulses, the phototube was cooled by alcohol and dry ice in excess. The lowering of the temperature was observed by counting the dark-pulses with a scale and mechanical recorder. A thermocouple at the surface of the multiplier indicated −80° C after half an hour, but only after two hours did the counting rate become constant, indicating that thermal equilibrium was attained.

The tube was operated with the wiring, shown in Fig. 1, with 800, 1000, and 1200 volts on the input, i. e. 70, 87, and 104 volts per stage. The cathode could be illuminated weakly by a battery-supplied incandescent lamp through a narrow aperture with a blue-filter. The pulses were photographed both with the light on and in the dark to obtain the background, Fig. 10, a–d.

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[8] See also W. SHOCKLEY and J. R. PIERCE, Proc. I. R. E. *26*, 321 (1938).

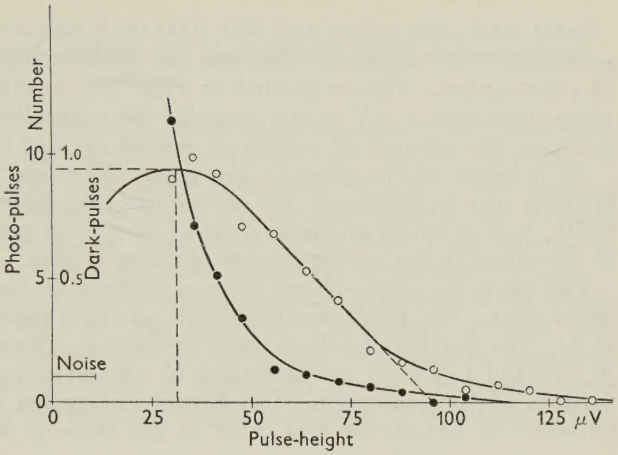

Fig. 3. Pulse distribution for 70 V, dry ice.
○ photo-pulses.
● dark-pulses.

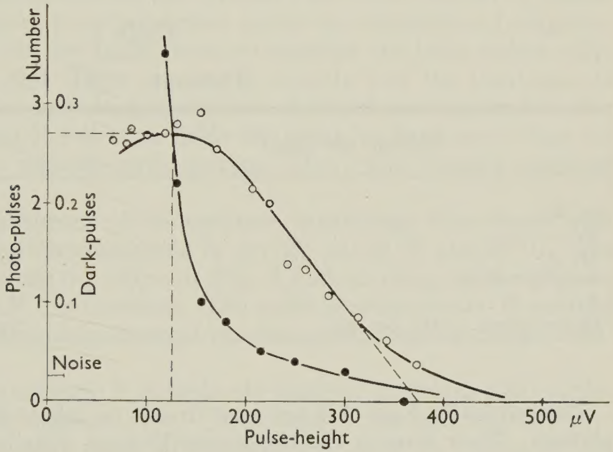

Fig. 4. Pulse distribution for 87 V, dry ice.
○ photo-pulses.
● dark-pulses.

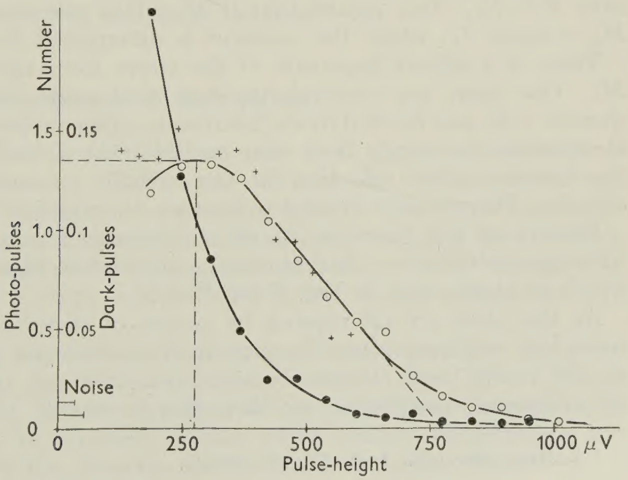

Fig. 5. Pulse distribution for 104 V, dry ice.
○ and + photo-pulses obtained at different amplification between multiplier and oscilloscope.
● dark-pulses.

2000–3000 light-pulses and 400–1000 dark-pulses were measured on the film in each case. The difference between the distributions is taken as the distribution of photo-pulses. This is plotted in Figs. 3–5 together with the background. The pulse-amplitude in µV at the anode of the multiplier is chosen as abscissa and as ordinate the number of pulses per second divided by the widths of the intervals.

As a result of the noise in the preamplifier and the finite cross-section of the brilliant spot on the screen, the ground line from which the pulses start has a certain width, half of which has been marked off on the graphs. It shows the magnitude of the errors in the measurements of pulse heights.

The plots for photo-pulses show a plateau at the ordinate M_y followed by a linear slope. The latter is extrapolated and cuts the ordinate at I_y and the abscissa at I_x. The quotient I_y/M_y is given in Table I. The curves of Fig. 2 have $I_y/M_y =$ $= 1.72$ and 1.92 for a multiplication $R = 3$ and 4 respectively, if M_y is taken as the position of the maximum. The R-value suggested by the experimental I_y/M_y is obtained by comparison and given in the table as R_I.

Table I

Data at — 80° C.

Voltage per stage	70	87	104
I_y/M_y	1.72	1.79	1.77
R_I	3.0	3.35	3.25
M_x µV	32	135	270
Amplification	$12 \cdot 10^3$	$50 \cdot 10^3$	$100 \cdot 10^3$
R_{II}	2.85	3.3	3.6
Photo-pulses $> M_x$ per sec.	360	380	400

The curves in Figs. 3–5 are now drawn to follow the linear slope and touch the plateau. Their form is the broadened Poisson distribution of the preceding section with $R = R_I$. This means that if M_x is the position of the expected maximum, $M_x =$ const. I_x, where the constant is determined from Fig. 2.

There is a salient departure of the curve from the plot at pulses smaller than M_x. One must not overlook the fact that some electrons leaving, for instance, dynode 1 do not reach dynode 2 but some other surface in the tube due to improper electrostatic focusing. It is also possible that a few photons strike dynode 1 — for instance after reflection in the cathode — and start avalanches from the dynode. These facts will tend to increase the number of small pulses.

ENGSTROM has, however, found a pronounced maximum and BAY[9] — using a 12-stage multiplier — has plotted a height-distribution in very good agreement with the ideal curve in Fig. 2 for $R = 5$.

As the plots are interpreted by means of statistical fluctuations in successive secondary emission after the arrival of one electron on dynode 1, the same curve should result from electron bombardment from an external source. According to an integrated distribution by BAY, this is roughly the case.

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[9] Z. BAY, Rev. Sci. Inst. *12*, 127 (1941).

Influence of temperature and voltage on photoelectric yield and secondary emission

If M_x is treated as the mean value of the pulses and it is assumed that each pulse arises from one photoelectron, the amplification of the tube can be computed by multiplying M_x by the collecting capacitance — roughly 60 $\mu\mu$F — and dividing by the electronic charge. The values obtained for the amplification are given in Table I. They are considerably smaller than those in the RCA Tube Handbook, but it is well known that the tubes show great individual fluctuations in data.

The mean multiplication factor R is now calculated as the ninth root of the amplification and given as R_{II} in Table I. The variation of secondary emission with voltage is characterised by the increase in R_{II}. R might, of course, be somewhat different at various dynodes, so the values of R_I and R_{II} are not incongruous when compared for the same voltage but certainly ought to increase more uniformly with voltage.

If it is assumed that the plateau reaches the ordinate, the total number of photopulses per second is easily obtained as the surface under the extrapolated diagram. It is, however, more practical for the applications to consider the large pulses only, for instance those exceeding M_x. Their number is roughly half the total, and is given in the table. Dependence on voltage is neither obtained nor expected — the light source being constant and the electric fields too weak to have more than an insignificant influence on the photoelectric process. BAY, too, found a constant yield by pulse-counting.

In order to determine the influence of temperature, recordings were made with 70 volts per stage for the same illumination as in dry ice but at 0° and 20° C. The plots form curves coinciding with the slope in Fig. 3 and starting at the plateau so that I_x, and consequently M_x, is constant. The multiplication factor R and the total amplification are therefore independent of the temperature in the range $-80°$ to $+20°$ C.

As the areas under the plots coincide it is probable that the quantum yield of the photo-surface for blue light is constant too. ENGSTROM's measurements of current, which were made over a wide range of temperature, show no change in the sensitivity i.e. the product of yield and amplification.

Distribution of dark-pulses

It is commonly assumed that the dark-pulses arise from thermionic emission of single electrons from the electrodes. The number of primary electrons from each dynode ought to be roughly the same as from the cathode. The amplification decreases, however, R times from cathode to dynode 1, from dynode 1 to dynode 2, etc. Assuming the pulse-height distribution from each electrode to consist of a plateau and a linear slope as in Figs. 3–5, the distribution of dark-pulses for $R = 3$ should follow Fig. 6.

Photographic recordings of the dark current at zero temperature give the plots in Fig. 7. The course at dry ice temperature was drawn in Figs. 3–5. There is general agreement with Fig. 6, but the experimental curves fall more rapidly with increasing pulse-height than is expected, a fact which cannot altogether be explained by the broadening of the diagram due to errors in measurements.

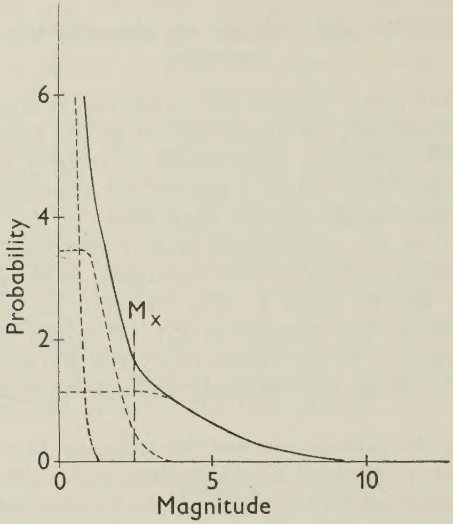

Fig. 6. Expected distribution of dark-pulses.

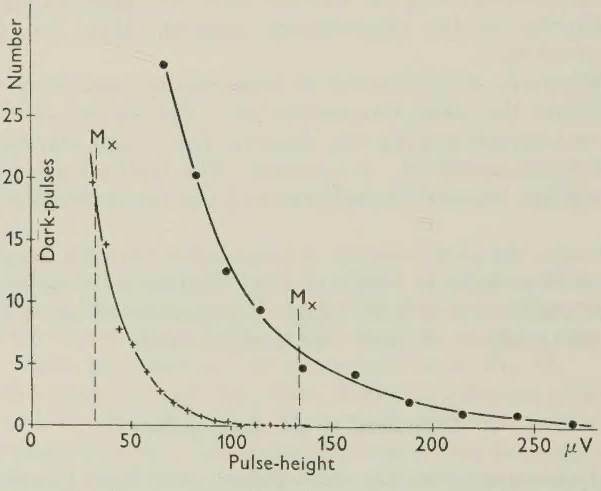

Fig. 7. Distribution of dark-pulses, 0° C. + 70 V, ● 87 V.

In order to settle the magnitude of avalanches starting from the dynodes only, MARSHALL, COLTMAN, and HUNTER[10] disconnected the cathode from the high-tension source. If the dynodes were kept at unchanged potential, but the cathode was connected with dynode 1, we found a considerable abatement of large pulses at room temperature, Fig. 10, e–f. The connection changes the operation of the tube in a complicated way. The difference between the distributions before and after the connection should, therefore, only roughly equal the distribution of pulses, initiated from the cathode. The difference plot seems, however, to be of fairly

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[10] F.-H. MARSHALL, J. W. COLTMAN, and L. P. HUNTER, Rev. Sci. Inst. *18*, 504 (1947).

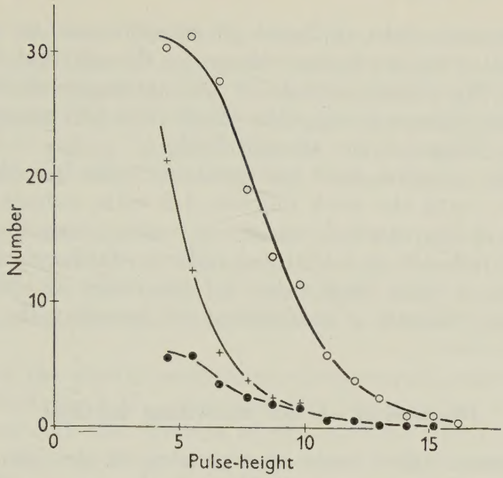

Fig. 8. Pulse distribution at room temperature, 70 V per stage, arbitrary units. ○ photo-pulses. + dark-pulses. ● cathode dark-pulses.

the same shape as the plot of photo-pulses, Fig. 8. This fact favours the assumption that the large dark-pulses are due to electron emission from the cathode.

At dry ice temperature the dynode-cathode connection caused only a slight change in the background. This suggests that the dark-pulses at this temperature are not essentially due to thermionic emission from the cathode. This fact might also be responsible for the discrepancy between the real diagrams in Fig. 7 and the ideal one in Fig. 6.

Number of dark-pulses as a function of temperature and voltage

The numbers of dark-pulses greater than M_x were obtained as the areas under the diagrams in Fig. 7 and Figs. 3–5. They are given in Table II. The values at 20° C and liquid air temperature come from pulse-counting with a discriminator and mechanical recorder. If we keep to the common explanation of dark-pulses, illustrated in Fig. 6, the numbers in the table should in every case form the same fraction (about one half) of the total number of pulses starting from the cathode. 10^3 cathode-pulses per second as in the tube under consideration seems to be an exceptionally low value at room temperature, 10^4–10^5 being found as a rule.

Table II

Number of dark-pulses per second greater than M_x.

Temp. °C	Voltage per stage		
	70	87	104
−185	—	~0.3	—
− 80	16	13	15
0	350	350	—
20	750	—	—

Contrary to ENGSTROM's data at liquid air temperature, no obvious increase in pulse-number is found with increasing voltage -- though that impression is easily obtained on viewing the screen because of the enhancement in pulse amplitude. Moreover, only a small change in Schottky-effect is to be expected from the theory of metals under this change of the electric field.

The decrease in the emission with temperature is far less than that prescribed by Richardson's law, using the work function 1.9 volts, calculated from the wavelength limit 6500 Å of the spectral sensitivity curve, given by the manufacturer. This fact, too, might indicate an additional pulse-initiating process that dominates at low temperatures. A very high value (of the order of 10^{12} amp/cm^2 deg^2 K) of the first Richardson constant A is obtained on inserting the room temperature data in Richardson's law.

Discussion of the recording method

Traces about 200 μsecs apart could be separated on the film, but even overlapping traces are measurable in most cases. If only pulses greater than M_x are counted from a dark current recording taken at room temperature, about 1000 pulses per second are found. If the resolving time of the preamplifier is 20 μsecs, the loss from electrical overlapping will be 2 %. The loss will be considerable if we try to measure smaller pulses, as their number increases rapidly with decreasing height. This is a serious limitation of the method. Only the fact that this particular tube possessed an uncommonly small dark current made it possible to take up curves at 20° and 0° C. But even for this tube the curves could not be followed below M_x.

Electrical counting methods permit the use of a fast amplifier and are therefore to be preferred at room temperature and when the intensity of light is strong. Much tedious work will also be spared if the measurement of traces on the film can be avoided.

For purposes of comparison, we registered pulses with a mechanical recorder, preceded by a scale and a Schmitt trigger circuit discriminator. Reproducable values were found that showed good agreement with the photographic measurements as long as the intervals were broad. Such was, however, no longer the case as they were made narrower when a detailed distribution curve was aimed at. The number of pulses was obtained as the difference between the counting rates at two different settings of the discriminator. They are measured at different moments of time. Even minute drifts in the voltages of the power supplies will, therefore, give erroneous results, if the interval is narrow so that the counting rates only differ slightly. A fast multi-channel differential discriminator should be the ideal instrument for the investigations in question.

At reduced voltage as, for instance, 70 volts per stage the internal amplification of the multiplier is low so that the noise from the preamplifier will no longer be negligible, but will contribute to the broadening of the distribution curves and make measurements of pulses much lower than M_x without significance. This drawback cannot be avoided even with electrical counting.

Photometric application

As pointed out by BAY, pulse-counting should be used if the sensitivity of the tube is to be pushed to the limit for weak intensities. A beam of light giving about the same number of pulses as the background may be measured. This means, for the tube under consideration, 15 pulses per second at dry ice and 0.3 at liquid air temperature, if we discriminate at M_x. If the quantum yield for blue light is 3 %*, roughly 1.5 % (compare Figs. 3—5) of the photons striking the sensitive area of the cathode will give pulses greater than M_x, so an intensity of 2000 and 40 blue photons per second may be measured, respectively, i.e. about 10^{-15} and $2 \cdot 10^{-17}$ watts.

The constancy of areas under the curves of dark-pulses and photo-pulses in Figs. 3–5 shows that the choice of voltage on the tube has no influence on the sensitivity of this method, i.e. the ratio between photo-pulse-number and dark-pulse-number. To avoid great external amplification a rather high voltage is recommended.

On the other hand, the discriminator bias relative to M_x must be carefully chosen. If the bias is pushed to $\frac{1}{2} M_x$, for instance, the number of dark-pulses is increased several times but the fraction of photo-pulses which is counted only from about $\frac{1}{2}$ to about $\frac{3}{4}$, thus resulting in an unfavourable discrimination. See Figs. 3–5.

Fatigue effect

As is well-known, the sensitivity of the multiplier phototube decreases markedly when it is irradiated with light of such intensity as to give an output current of the order of milliampères, but recovers after storage in the dark for a couple of days.

In order to find out how the distribution curves change during illumination the pulses were photographed in the dark and during irradiation by a weak source of light. The intensity of light was increased and the output current kept at 0.1 mA for 10 minutes. Then the weak light and the background were recorded once again. The tube was cooled by dry ice and operated at 87 volts per stage.

The results are plotted in Fig. 9. The photo-curve before illumination is drawn by the same method as that for Fig. 4. After illumination the distribution is pushed towards smaller pulses so that the plateau is not reached in the measurements. The maximum expected is taken from the intercepts of the linear slope of the plot with the axis using the relations $I_y/M_y = 1.72$ and $I_x/M_x = 3.0$, taken from the curve $R = 3$ in Fig. 2.

The decrease in M_x from 110 to 75 gives a measure for the fatigue of the tube. The effect is probably caused by a loss in the multiplication factor at dynodes 8 and 9 that are subject to a rather heavy bombardment of electrons. A thorough discussion is given by MARSHALL, COLTMAN, and HUNTER.

The number of photo-pulses greater than M_x — i.e. the area under the slope in the diagram — is 1100 before and 1400 after irradiation. The discrepancy is probably due to an error in the realigning of the weak light source, but it is of course not out of the question that there might be an increase in quantum yield as a result of the illumination. The experiment should be repeated carefully.

The increase in the number of dark-pulses is hard to explain from thermionic emission, for the rise in temperature of the electrodes — even of dynode 9 — must in this case be moderate.

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* According to RCA-data, the sensitivity of a typical tube in the blue-violet is of the order of 10^4 μA/μW at 100 volts per stage. The amplification is 10^6 times and the energy of a blue photon $5 \cdot 10^{-12}$ erg. This gives 3 electrons per 100 quanta.

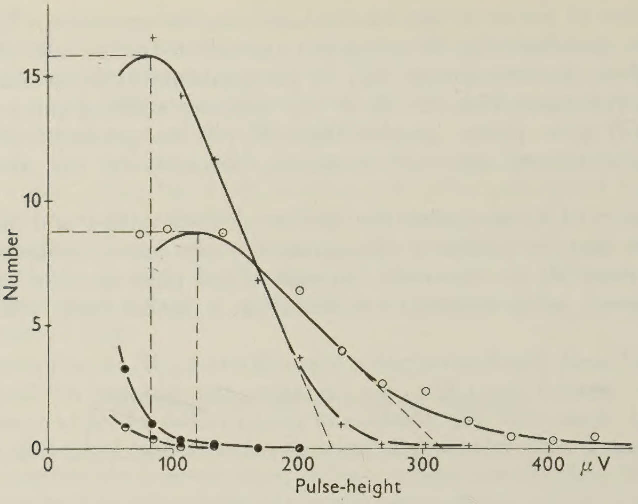

Fig. 9. Pulse distribution, showing fatigue effect at 87 V and dry ice temperature. ○ photo-pulses before irradiation. ◓ dark-pulses before irradiation. + photo-pulses after irradiation. ● dark-pulses after irradiation.

There are large fluctuations from tube to tube in the characteristic constants so the values obtained are not applicable for another multiplier. The intention of this report has been to show the power of the pulse-counting method for registering small intensities of light and to investigate the discrimination of light-pulses from dark-pulses under different conditions of operation.*

We wish to express our thanks to Professor ERIK HULTHÉN for his keen interest in the work and to Svenska Atomkommittén for financial support.

Physical Institute,
University of Stockholm,
January 1949.

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* After the accomplishment of the present investigation a paper of MORTON and MITCHELL, R. C. A. Review, Dec. 1948, became known to us. These authors have investigated pulse-distributions by somewhat different methods than those reported above.

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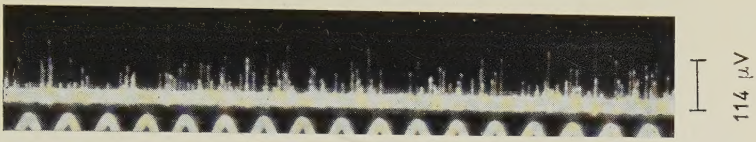
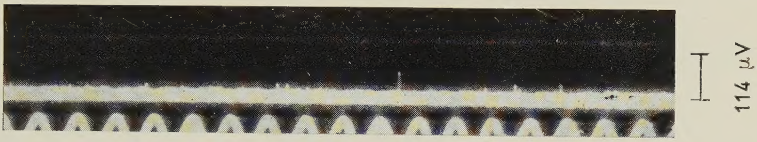
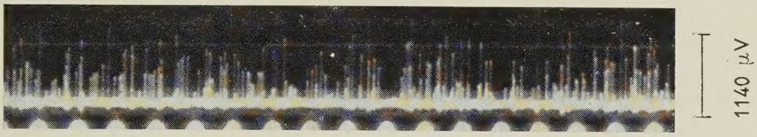


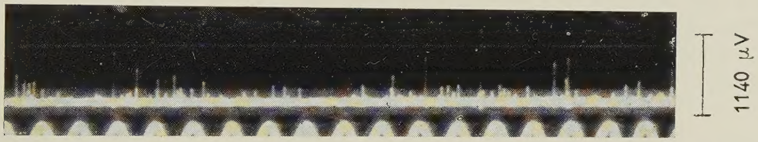
a. Dry ice, 70 volts, illumination.



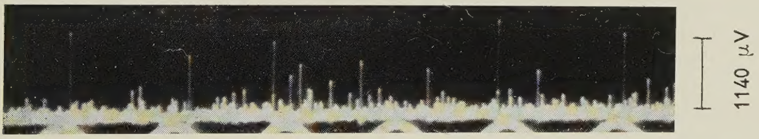
b. Dry ice, 70 volts, in darkness.



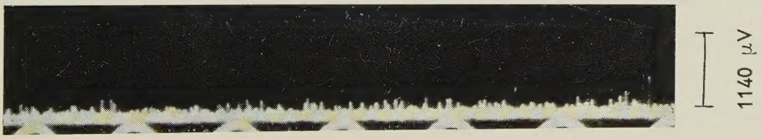
c. Dry ice, 104 volts, the same illumination as in a.



d. Dry ice, 104 volts, in darkness.



e. Room temperature, 87 volts, in darkness.



f. Room temperature, 87 volts, in darkness, cathode and dynode 1 connected.

Fig. 10. Film-recordings of multiplier pulses. Time-marking 50-cycles alternating current.